

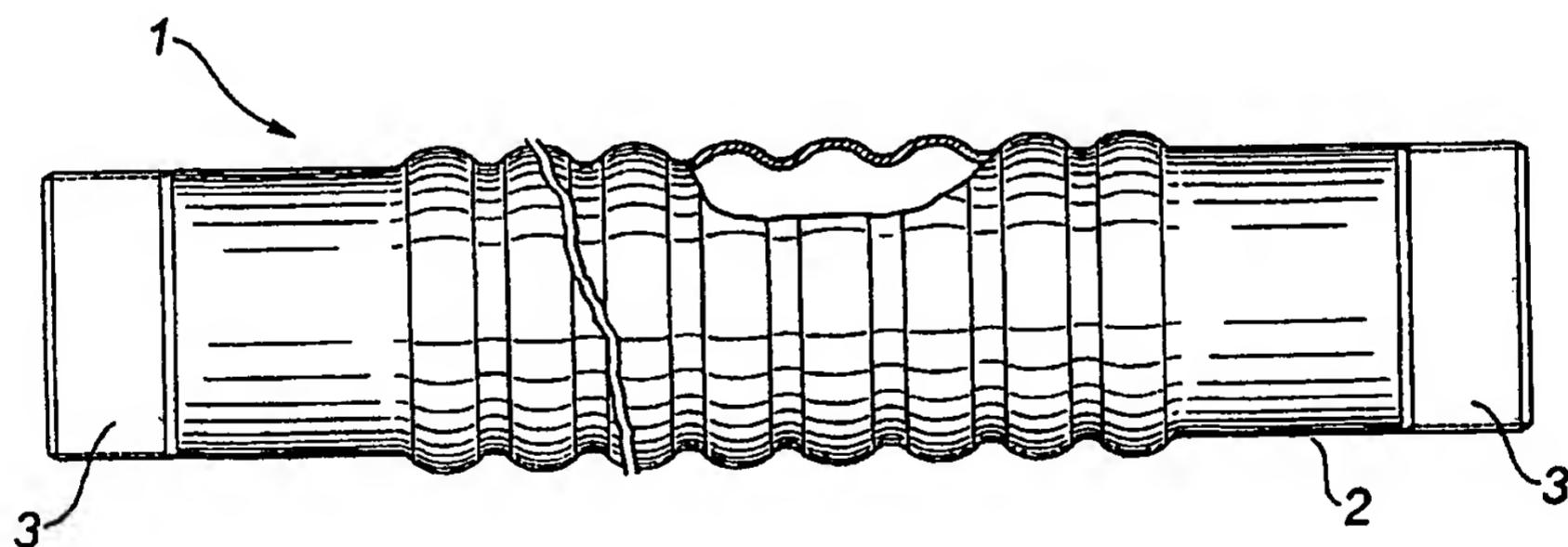


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(71) Applicant: NOETIC ENGINEERING INC. [CA/CA]; P.O. Box 49036, 9647 - 41 Avenue, Edmonton, Alberta T6E 6H4 (CA).	
(71)(72) Applicants and Inventors: SLACK, Maurice, William [CA/CA]; 1831 - 104A Street, Edmonton, Alberta T6J 5C1 (CA). KAISER, Trent, Michael, Victor [CA/CA]; 10912 - 16 Avenue, Edmonton, Alberta T6J 5G6 (CA). BEAULAC, Gerald, Adrien, Joseph [CA/CA]; 11126 - 23A Avenue, Edmonton, Alberta T6J 4N9 (CA).	
(74) Agent: JOHNSON, E., Peter, Ogilvie and Company, 1400 Canadian Western Bank Place, 10303 Jasper Avenue, Edmonton, Alberta T5J 3N6 (CA).	

(54) Title: CORRUGATED THICK-WALLED PIPE FOR USE IN WELLBORES



## (57) Abstract

Thick-walled steel pipe is corrugated for the purpose of managing axial load when the pipe is used in an earth-restrained application. For example, the pipe may be used as casing in a cyclic steam stimulation well, where the axial loads are induced as the casing is heated and cooled.

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1                           **"CORRUGATED THICK-WALLED PIPE**  
2                           **FOR USE IN WELLBORES"**

3                           **FIELD OF THE INVENTION**

4                           The present invention relates to corrugated pipe and its use in tubular  
5                           strings conveying fluid through earth material, for example as part of a buried  
6                           pipeline or casing in a well.

7

8                           **BACKGROUND OF THE INVENTION**

9                           The invention was initially developed as a means to reduce thermally  
10                          induced axial load in the production casing string of a well undergoing cyclic  
11                          steam stimulation. The production casing strings in such wells are normally  
12                          cemented in place and are therefore largely constrained from expanding or  
13                          contracting axially during heating and cooling cycles. This constrained  
14                          thermal strain is manifested as axial load which becomes more compressive  
15                          during heating and more tensile during cooling. Depending on the thermo-  
16                          mechanical material properties of the casing and the magnitude of  
17                          temperature cycling, the axial stress may exceed the axial yield strength of  
18                          the pipe in compression during heating and may exceed the axial yield  
19                          strength in tension during cooling. Among other consequences, the high  
20                          stresses place severe demands on the structural and sealing capacity of the  
21                          tubular connections between casing joints and significantly reduce the ability  
22                          of the pipe body to withstand collapse, bending and shear loads which may  
23                          arise from various hydraulic and geomechanical factors. The incidence of  
24                          leakage, fracture and access impairment 'failures' is therefore relatively high in  
25                          connection with the casing of thermal process wells.

1       Approaches taken by the industry to address this problem have  
2       typically included improving the strength and leakage resistance of the  
3       connections by utilizing more complex designs, for example substituting  
4       premium connections for the standard 8-round or buttress threadform  
5       connections, or increasing the grade of steel used. These approaches, while  
6       potentially providing significantly better seepage control and modest  
7       incremental structural performance, tend to increase cost and do not  
8       substantially reduce the risk of fracture or deformation induced failure.

9       Therefore there remains a need to address the primary confounding  
10      variable, namely the high axial stress induced by confined thermal expansion  
11      and contraction.

12      While thermal well design has been the primary motivator for the  
13      present invention, it is not to be limited to this application. The invention finds  
14      use in situations where there is interaction of loads between tubulars,  
15      surrounding earth material and contained or excluded pressure fluids, and  
16      where it would be desirable to increase axial or flexural compliance, decrease  
17      effective axial yield load and increase collapse resistance. One such situation  
18      involves buried pipelines. Here axial and flexural strain due to tubular-soil  
19      interaction must be absorbed without loss of pressure integrity. It would be  
20      desirable to provide tubulars of reduced axial and therefore flexural stiffness  
21      because these properties result in lower axial and bending loads than straight  
22      pipe for the same temperature variations and deformation magnitude.

1

SUMMARY OF THE INVENTION

2        The phrase "string of joints" as used herein is intended to encompass a  
3        plurality of joints of metal pipe, usually steel, connected end to end either by  
4        welding or threaded connections and to further encompass a sand exclusion  
5        liner if such is part of the string. The phrase "thick-walled pipe" is intended to  
6        mean high pressure pipe useful as oil country tubulars, such as casing and in  
7        high pressure pipelines, said pipe having a diameter to wall thickness ratio  
8        ("D/t") less than 100, preferably less than 50.

9        The present invention applies a well known mechanical design  
10      concept, corrugations, to thick-walled metal pipe which is to be used in earth-  
11      restrained applications, such as in a string of joints used as casing in a well or  
12      as part of a pipeline. The corrugations are incorporated for the purpose of  
13      managing changes in axial load subsequent to installation.

14       More specifically, the invention involves forming thick-walled pipe to  
15      convert at least part of its straight side wall into a corrugated configuration.  
16      The corrugations are formed so as to have a corrugation radius of curvature  
17      to thickness ratio ("R/t") less than 10, preferably less than 5. Preferably the  
18      corrugation webs have a maximum angle equal to or greater than 20° with  
19      respect to the pipe axis. More preferably the corrugations have thinned webs  
20      and flattened peaks. Preferably, the pipe is hydroformed, without  
21      substantially changing its original length, to create the corrugations. By  
22      selecting the geometry defined by these limitations we have balanced axial  
23      compliance (i.e. reduced axial stiffness) with diametral limitations arising from

1 the cost of increasing annular space consumed in a wellbore and material  
2 strain capacity.

3 Broadly stated then, in one embodiment the invention is concerned  
4 with a string of joints of thick-walled pipe extending through and being  
5 restrained by earth material, the string being subject to a change in axial load  
6 subsequent to installation, the side wall of at least one such joint having been  
7 formed into corrugations along at least part of its length, the corrugations  
8 having an R/t ratio less than 10. Preferably, one or more of the following  
9 conditions apply:

- 10 • the string is used in a well and is subject to changes in axial load  
11 arising from thermal expansion or contraction (for example where  
12 the well is involved in cyclic steam stimulation) or from earth  
13 movement;
- 14 • the string forms part of a buried pipeline;
- 15 • the R/t ratio is less than 5;
- 16 • a plurality of corrugated joints are distributed in spaced apart  
17 alignment along the string;
- 18 • the corrugation webs have a maximum angle equal to or greater  
19 than 20° relative to the pipe axis;
- 20 • the wall thickness of the webs of the corrugations are thinner than  
21 the peaks;
- 22 • the corrugations having been formed by hydroforming, more  
23 preferably without substantially changing its original length.

1        In another embodiment, the invention is concerned with a thick-walled  
2    steel pipe having threaded ends, the body of the pipe between the ends  
3    having been hydroformed to produce corrugations along at least part of its  
4    length, the corrugations having an R/t ratio less than 10. Any of the  
5    previously mentioned preferred conditions also may be incorporated.

6

7                    **DESCRIPTION OF THE DRAWINGS**

8        Figure 1 is a partially cut-away side view of a corrugated casing joint  
9    having threaded ends;

10       Figure 2 is a side view showing casing joints in accordance with the  
11    invention incorporated into two casing strings in a thermal horizontal well;

12       Figure 3 is a side view showing an alternative arrangement of  
13    corrugated joints;

14       Figure 4 is a partially sectional side view of a joint of straight-walled  
15    pipe installed in tri-axial plane strain hydroforming apparatus, prior to  
16    application of forming pressure;

17       Figure 5 is similar to Figure 2 after the joint has been formed to provide  
18    corrugations;

19       Figure 6 is a longitudinal sectional side view of the corrugated joint as  
20    formed under plane strain conditions, showing thickness variations; and

21       Figure 7 is a side view of part of Figure 6, showing corrugation and  
22    pipe geometry parameters.

1                   DESCRIPTION OF THE PREFERRED EMBODIMENT

2                   While recognizing the likely benefits of corrugated arth restrained  
3                   tubulars used for pipeline and well bore casing applications, the present  
4                   invention also required a means to place corrugations in the metal tubular  
5                   materials typically employed for these purposes. It was therefore desirable to  
6                   devise a manufacturing or forming process capable of creating suitably  
7                   shaped corrugations in the wall of standard casing and high pressure pipeline  
8                   materials of more or less full standard joint length. Such tubulars have a D/t  
9                   ratio less than 100, preferably less than 50. It was particularly desirable to  
10                  discover a process suited to casing tubulars for use in well bores in a manner  
11                  providing a geometry yielding suitable stress and strain behaviour under  
12                  installation and operational loads within the allowable annular space.

13                  Machining and forming are two techniques well known as means  
14                  capable of producing corrugation geometries in metal tubulars. Machining  
15                  provides a means to produce corrugation geometries of almost any desired  
16                  shape, but it is difficult to implement on the internal surfaces of casing  
17                  intervals beyond a few diameters of the tube ends. This technical difficulty,  
18                  combined with the relatively high cost of machining compared to forming,  
19                  makes forming or forming combined with only external machining the  
20                  preferred alternative.

21                  Existing methods for forming corrugated pipe or bellows from straight  
22                  tube may generally be divided into rolling and hydroforming or hydrofolding  
23                  processes. Rolling methods are used on thin-walled material having smaller  
24                  diam ter than that employed for casing or high pressure pipeline tubulars.

1 While other variations of rolling are applicabl to larger thickness s, wh r for  
2 example an internal spiral grooved mandrel is placed on the inside of the pipe  
3 and external rollers are used to deform the pipe into the mandrel grooves,  
4 such localized forming methods do not enjoy the simplicity of the global  
5 forming accomplished with hydroforming.

6 It should be pointed out that forming corrugations in spiral welded pipe  
7 by placing corrugations in the strip prior to or during the welding process  
8 offers another realistic forming process for larger diameter high pressure  
9 pipeline tubulars. Of course this method cannot be applied to tubes and is not  
10 suitable for smaller diameter pipeline and casing sizes.

11 The manufacture of corrugated pipe or bellows for applications such as  
12 pipeline expansion joints, by hydroforming or hydrofolding, is a technique well  
13 known in the art. As described in US patent 4,193,280, "In a process of this  
14 kind, the operation starts with a sheet-metal sleeve of a length greater than  
15 that of the bellows to be obtained, the said length being, in fact, equal to the  
16 developed length of the cylindrical ends of the said bellows and of the  
17 deformable corrugations therebetween. A series of suitably spaced rings is  
18 applied to the outer wall of the sleeve, which is preferably provided with end-  
19 flanges, and it is then placed upon the fixed platen of a press. The interior of  
20 the sleeve is filled with a liquid which escapes at a controlled rate and the  
21 press is operated in such a manner that the mobile platen is applied to one  
22 end of the assembly. The partially confined liquid inside the sleeve develops  
23 an internal pressure and, assisted by the axial load, causes the metal to

1 deform outwardly between the forming rings, so that the bellows is eventually  
2 shaped."

3 As described, this technique does not contemplate application to  
4 casing and high pressure pipeline tubulars which have relatively smaller  
5 diameter to thickness (D/t) ratios than the pipe materials to which it is usually  
6 applied, described as a "sheet metal sleeve". Further, this description shows  
7 that the method as presently practiced does not contemplate changing the arc  
8 length of the shaped pipe, in that "the developed length" is expected to be the  
9 same as the initial "sheet metal sleeve" length. While the method does  
10 provide for direct control of corrugation period through selection of ring  
11 spacing and amount of axial compression, these parameters simultaneously  
12 control amplitude to a large extent. Little additional control of corrugation  
13 shape is possible beyond contouring of the confining rings and the natural  
14 unrestrained toroidal bulge formed between the rings. Control of wall  
15 thickness distribution is not considered as indicated for example by the use of  
16 the term "hydrofolding" and by the expectation that "the developed length"  
17 remains unchanged which can not in general be the case if thickness is to be  
18 varied. However for application to casing and high pressure pipeline tubular  
19 corrugation, it is desirable to obtain corrugations without dramatic changes in  
20 original tubular length, to more independently control period and amplitude  
21 and to control aspects of the local corrugation geometry variables such as  
22 shape and thickness.

1        Before considering how the modified hydroforming process of the  
2 present invention may be used to overcome these difficulties and limitations  
3 and provide other advantages, it is desirable to consider the relationship  
4 between these corrugation geometry variables and corrugated casing  
5 performance. It is thus also desirable to consider how the corrugations to be  
6 introduced into casing materials differ from the accepted understanding of  
7 corrugation geometry.

8        As a term well accepted in the art, a pipe corrugation is generally  
9 meant to describe a wrinkle or wave in the wall of otherwise cylindrical tubes.  
10 Such corrugations commonly go from peak to valley to peak to valley etc.  
11 along all or some portion of the pipe length and, even when helical, are largely  
12 circumferential in orientation. This understanding also carries the assumption  
13 that the material thickness does not vary substantially along the wave and that  
14 these pipes may be treated as shells for stress analysis purposes. Such  
15 corrugations or bellows may be treated as shells, and design characteristics  
16 such as stress and displacement response to load obtained using standard  
17 treatments, such as given, for example, by W.C. Young, "Roark's Formulas  
18 for Stress and Strain", Sixth Edition, McGraw Hill Inc., 1989, pg 570. However  
19 such treatments break down where the ratio of corrugation radius of curvature  
20 to thickness becomes small. In the given reference, this occurs for R/t ratios  
21 less than 10.

1           While the term corrugation is applied herein to convey the general  
2   sense of the modified casing wall geometry intended to provide the benefits of  
3   the present invention, the peculiar requirements of the well bore casing  
4   application require corrugation geometries substantially outside the  
5   understandings of corrugations usual to the art. To provide corrugations with a  
6   significant reduction in axial compliance and yield load as needed for the  
7   intended applications, it is generally desirable to create corrugations with a  
8   maximum web angle greater than about 20° with respect to the pipe axis. To  
9   stay within reasonable amplitudes, and to further optimize the stress and  
10   strain distributions by varying the wall thickness over the corrugation interval  
11   or wavelength, this implies a radius of curvature to thickness ratio  
12   substantially less than 10, preferably less than 5, is needed. It is therefore  
13   necessary to consider the corrugations to be placed in casing or pipeline  
14   tubular walls as *thickwall* corrugations and to obtain estimates of performance  
15   determining stress and strain variables accordingly.

16           As will be evident to one skilled in the art, the corrugation amplitude is  
17   constrained to occur within the annular clearances allowable by both outer  
18   and inner confining surfaces, typically the well bore wall and production tubing  
19   respectively, plus additional running and cementing clearances. Within this  
20   constraint, the corrugation geometry produced to obtain the desired reduction  
21   in axial stiffness must still provide for sufficient strength to run the tubular, and  
22   perhaps react pressure end load. While meeting these basic requirements it is  
23   further desirable to obtain a geometry which will produce an axial load  
24   significantly lower than occurs with cylindrical pipe when heated, but not at the

1 expense of high cyclic plastic strain, a parameter that strongly controls th  
2 corrosion fatigue failure response. To obtain significant stiffness reduction, th  
3 angle of the pipe wall portion falling between the peaks and valleys of the  
4 corrugation, referred to here as the corrugation web, should be increased  
5 substantially, typically above 45° with respect to the axis. This necessitates  
6 relatively sharp curvatures in the peak and valley regions to prevent  
7 amplitudes exceeding the available annular space. For casing and high  
8 pressure pipeline tubulars these curvatures result in R/t ratios nearer 1 than  
9 10, placing such corrugations well beyond the limits of standard membrane  
10 stress analysis treatments. Particularly at the peak locations, this tends to  
11 result in severe flexural stress or strain concentrations under axial loading if  
12 typical toroidal geometries are employed. It is therefore beneficial to provide a  
13 geometry where the peaks are somewhat flattened to distribute the flexural  
14 strain over a longer interval. It is further beneficial to provide a geometry  
15 where the web portions of the wall are somewhat thinner, providing a further  
16 improvement of stress distribution and lower axial stiffness within the same  
17 annular space constraint. Because the flexural wall stiffness is a very strong  
18 function of thickness (proportional to the third power of thickness for elastic  
19 deformations) apparently small variations in thickness appear to have a  
20 disproportionately large effect on stress distribution.

1       Control of such geometry considerations, arising as they do from the  
2    thick wall nature of casing corrugations, are not generally contemplated in  
3    existing hydroforming processes. As already discussed, the corrugations to be  
4    formed by these existing processes are largely constant thickness, toroidal at  
5    peaks and valleys and thin wall in nature. The term '*triaxial hydroforming*' has  
6    therefore been adopted herein to describe the more specialized process  
7    needed to produce casing containing thick wall corrugations better suited to  
8    earth-restrained tubular design requirements. This process typically requires  
9    higher pressures, greater control of the axial load and is more sensitive to  
10   friction behaviour between the tubular and confining mold than hydrofolding  
11   where compressive load is primarily used to cause internally pressurized pipe  
12   to buckle between confining rings.

13       It has been found that triaxial hydroforming conducted under global  
14    plane strain conditions, where the corrugations are formed by application of  
15    high internal fluid pressure while the overall pipe length is kept constant,  
16    produces a corrugation geometry well suited to thermal strain absorption. In  
17    this case the axial force is in fact tensile during forming, and the resulting  
18    plastic material flow which is further controlled by contact and friction induced  
19    stress between the pipe and form, produce an advantageous thinning in the  
20    web region of the corrugation during forming of the corrugation 'bulge' under  
21    pressure.

1        But this is just one combination of axial load or displacement and  
2    pressure or fluid volume control. Other combinations are possible as for  
3    example would occur if no axial load were applied (plane stress) and forming  
4    was completely accomplished by the application of internal pressure causing  
5    bulges to form between rings as commonly used for hydroforming. Such  
6    variants of the pressure axial load relationship may be manipulated to  
7    produce geometries having characteristics suitable for particular applications  
8    and to simultaneously control the change in overall tubular length caused by  
9    the forming process.

10       The simplicity of the triaxial plane strain forming process used to  
11    produce this corrugation geometry of the preferred embodiment, lends itself  
12    particularly well to modest manufacturing cost and small annular space  
13    requirements. The resulting tubular architecture is well suited for use in wells  
14    using the cyclic steam stimulation production method, as well as other  
15    applications benefiting from tubulars with reduced axial load or greater strain  
16    absorption to prevent the instabilities associated with global plastic  
17    deformation. The plane strain condition enjoys the further advantage of  
18    maintaining the original joint length which facilitates interchangeability  
19    between corrugated and straight tubulars.

20       From the foregoing, it should be apparent to one skilled in the art, that  
21    the fundamental triaxial process variables of confining mold shape, axial load  
22    or strain, internal pressure and contact friction, enables a pipe corrugation to  
23    be configured with significant control over both the corrugation amplitude as a  
24    function of axial length and its thickness distribution to help control stress and

1 strain response to meet a large spectrum of design requirements for earth  
2 restrained tubular systems. However corrugation shape obtained by plane  
3 strain hydroforming provides a particularly well conditioned corrugation shape  
4 for application to cyclic steam stimulation well completion applications as  
5 anticipated in the preferred embodiment.

6 The placement of suitable corrugations in the tubular wall is supported  
7 through provision of a specialized hydroforming process providing a means of  
8 creating axially compliant corrugation geometries without substantial internal  
9 machining which process employs control of axial length during hydroforming  
10 and is therefore capable of controlling the change in the length of the tubular  
11 being formed. The hydroforming process comprises the steps of:

- 12 • placing a length of cylindrical tube inside a confining surface comprised  
13 of elements spaced and shaped to control the joint geometry to  
14 generally have corrugations in the mid-section and cylindrical end  
15 sections and contained within a confining tube supporting or guiding  
16 the elements creating the confining surface;
- 17 • applying sufficient internal pressure to force the tubular wall radially  
18 outward against the confining surface while simultaneously controlling  
19 the axial length of the tubular during and after application of internal  
20 pressure and thus plastically form the tubular article where such axial  
21 length control is preferably such that the original tubular length is  
22 substantially preserved or unchanged;

1       • removing the formed corrugated tubular joint from the forming  
2       apparatus which removal may be facilitated by the application of  
3       external pressure sufficient to free the article from the confining  
4       surface; and

5       • additionally finishing the formed joint, if required, by external machining  
6       of the corrugations to further control the final geometry or machining of  
7       the cylindrical ends to provide for joining by threaded connections,  
8       welding or other joining method.

9       In its preferred embodiment, joints 1 of corrugated tubular are provided.  
10      The joint has cylindrical ends 2 to facilitate joining, using industry standard  
11      methods such as welding for pipelines or threaded connections for well bore  
12      casing. Such a joint of corrugated casing is shown in Figure 1 with threaded  
13      pin ends 3. The diameter and wall thickness of the cylindrical ends 2 are  
14      chosen to ensure compatibility with industry sizing standards. The cylindrical  
15      end length would typically be chosen to allow for gripping with standard  
16      connection make up and handling equipment. In certain cases other  
17      operational or completion requirements such as packer setting locations may  
18      dictate longer cylindrical intervals at the ends or additional cylindrical sections  
19      elsewhere along the joint length. Also, as shown in Figure 1, the corrugation  
20      valleys are arranged to coincide with the nominal pipe internal diameter so  
21      that the corrugation amplitude has the effect of increasing the effective pipe  
22      body diameter. While it is expected this configuration will be desirable for  
23      most applications, a corrugation valley diameter less than the nominal pipe  
24      diameter may also be provided.

1        The triaxial plane strain hydroforming process preferred to provide such an  
2        article of corrugated casing requires an apparatus 4 such as shown in Figure  
3        2. In this apparatus 4, a confining tube 5 is provided with sealing annular end  
4        closures 6 and a contoured form 7. The form 7 comprises elements providing  
5        cylindrical end sections 8 and a centre corrugating section 9 closely fitting  
6        inside said confining tube 5. The tube 5, end closures 6 and contoured form 7  
7        together comprise a forming vessel 30. A forming fluid access port 10 is  
8        provided in one annular end closure 6. A mandrel 11 with external end seals  
9        12 and a forming fluid access port 13 is also provided.

10       The centre corrugating section 9 is constructed of various axisymmetric  
11       ring and sleeve elements 14, 15 as shown in Figures 2 and 3. To facilitate  
12       removal after forming, some or all of these elements 14, 15 are split. Element  
13       shapes comprising the forming profile are selected to provide a distribution of  
14       void space into which the tubular material is caused to flow under the  
15       application of internal pressure. Friction forces activated by contact stress  
16       between the confining surface and casing joint 16 also contribute to  
17       controlling plastic flow during forming. For a given tubular, the final  
18       corrugation shape is thus controlled by void space distribution, lubrication or  
19       friction coefficient in the interfacial region between the casing joint 16 and  
20       form 7 and forming pressure.

21       The cylindrical end sections 8 have an internal diameter only slightly larger  
22       than the outside diameter of the casing joint 16 to be formed to provide casing  
23       joint end sections 2 of standard dimensions suitable for threading and  
24       handling. The end sections 8 need not be split to allow removal. If desired, the

1 ring and sleeve elements 14, 15 of the centre corrugating section 9, and  
2 indeed the cylindrical end sections 8 as well, may all be provided as a single  
3 split half form. This configuration of the form or mold permits more rapid  
4 assembly and disassembly where repeated forming is required.

5 As shown in Figure 2, the casing joint 16 is placed inside the forming  
6 vessel 30 and the mandrel 11 is placed inside the casing joint. The mandrel  
7 11 provided with seals 31 for sealing against the inside surface 31 of the  
8 casing joint 16 at two locations, typically near the joint ends. The seals 32 are  
9 spaced to provide an interval of the casing joint, inside the forming vessel 30,  
10 that may be internally fluid loaded to a pressure causing the casing material to  
11 plastically expand outward. Similarly the annular end closures are provided  
12 with seals 33 to seal between the casing joint exterior and confining tube end  
13 closures 6 at nearly the same axial position as the mandrel seals 32, so that  
14 the casing joint may be externally pressured over the same interval.

15 Thus arranged, the apparatus 1 is used to form the casing joint 16 by first  
16 applying internal pressure, beyond the pipe body yield, to expand the casing  
17 material outward against the inside surface 38 of the corrugating section 9.  
18 The inner contoured form of the forming vessel 30 is provided to control the  
19 shape of the external expansion of the casing material so that as internal  
20 pressure is increased the casing material will be progressively forced into  
21 contact with the profiled surface 38 as shown in Figure 3.

1        As shown in Figure 3, the casing joint length is not substantially reduced  
2        by this process as in typical hydroforming or hydrofolding processes used to  
3        provide corrugated pipe. It will be clear that the plane strain forming condition  
4        requires the development of axial tensile stress as the corrugations 34 are  
5        formed. The apparatus 1 reacts the resulting force through friction forces  
6        developed along the cylindrical end sleeves. The friction forces are enabled  
7        by contact stress between the internally pressurized casing material and the  
8        confining form end sections 8 as pressure is initially increased beyond that  
9        required to initiate yield and close the relatively small installation gap provided  
10      between the casing joint and form end sections 8. Further increases of  
11      pressure are used to cause flow into the corrugation voids to the extent  
12      required to form corrugation geometries providing substantial reductions in  
13      tubular axial compliance, where the pressure required to cause such  
14      deformation magnitudes will typically exceed the casing material yield  
15      pressure by several times.

16      Following forming under these high pressures, the residual contact stress  
17      between the casing joint 16 and contoured form surface 38 tends to preclude  
18      straightforward removal of the casing joint 16 from the forming vessel 30.  
19      Therefore the forming process is completed by applying sufficient external  
20      pressure through port 10 to plastically yield the casing joint and cause inward  
21      radial deformation to form a gap between the joint and contoured form surface  
22      38 and thus substantially eliminate the residual contact stress inhibiting  
23      removal. The pressure and sealing capacity of the annular end closures 6 and

1 seals 33 need only provide sufficient containment to cause global pipe body  
2 yield.

3 Following application and removal of external pressure, the mandrel and at  
4 least one end cap are removed. The casing and contoured form are then  
5 removed and finally the elements of the form removed from the casing. The  
6 process may be repeated to form additional joints of formed pipe.

7 In certain applications, the utility of the corrugated pipe formed by this  
8 process may be further enhanced by heat treatment, such as annealing for  
9 steel, after forming. This may be needed because the amount of plastic  
10 deformation imposed by the forming process may affect performance  
11 properties such as corrosion sensitivity, fatigue life or simply remaining plastic  
12 capacity.

13 A typical thickwall corrugation geometry of the casing joint shown in Figure  
14 1, and formed by the plane strain tri-axial hydroforming process, is shown in  
15 Figure 4. This figure shows a cross section through several corrugations 34.  
16 The relatively subtle variations in thickness obtained using the triaxial forming  
17 process are evident. Stress analysis of this geometry using the finite element  
18 method was used to calculate a reduction in axial stiffness of approximately 5  
19 times that of the original non-corrugated straight pipe.

20 Example

1 To illustrate the utility of the present invention in reducing thermally  
2 induced axial load, consider a well where cylindrical steel casing with yield  
3 strength of 550 MPa is cemented at 20° C with negligible axial load and is  
4 subsequently heated to 250° C. Typical properties for the thermal expansion  
5 coefficient and elastic modulus of casing steel are 12  $\mu$ e/C and 200 GPa  
6 respectively. For such a material, provided its elastic limit is not exceeded, the  
7 axial stress increase upon heating is calculated from the relation,

8 Axial stress = temperature change  $\times$  expansion coefficient  $\times$  elastic  
9 modulus = 552 MPa.

10 The casing will thus be just at its yield load with consequent deleterious  
11 impact on connection and pipe body resistance to failure. However in this  
12 same application, casing with corrugations such as shown in Figure 4 over  
13 most of its length would reduce this load by a factor of nearly 5, reducing the  
14 axial stress to 110 MPa, placing the casing and connections in a much more  
15 favorable load operating regime.

16 As an alternative to hydroforming by application of internal pressure to  
17 expand a tubular against an external form as described in the preferred  
18 embodiment, this process may be inverted to apply external pressure to the  
19 tubular and providing a form internal to the tubular. In this case the form would  
20 typically be configured to provide spiral corrugations to facilitate removal.

1        In another aspect, we believe the properties of corrugations provided  
2    by the tri-axial hydroforming process may be further improved for certain  
3    applications through selectively removing material by external machining  
4    either before or after hydroforming. For example such machining can be used  
5    to further thin the web thickness and extend the range of available elastic  
6    deformation.

7        In another aspect, a cylindrical liner with a first and second end is  
8    provided on the interior of a corrugated tubular joint with first and second ends  
9    where the first end of the liner is joined/fastened to the first end of the  
10   corrugated tubular joint and said liner extends to cover all or a portion of the  
11   corrugated interval. This configuration permits telescopic sliding of the straight  
12   liner relative to the corrugated tubular to provide a system retaining the axial  
13   compliance of the corrugated tubular but having increased flexural stiffness  
14   and therefore buckling stability, reduced flow losses, simpler cleaning with  
15   pigs or wiper plugs and a smooth surface for sealing of devices such as  
16   packers. In a further aspect of such a corrugated tubular with internal liner the  
17   second end of the liner and second end of the tubular may be provided with  
18   interlocking stop rings or similar devices permitting the telescopic relative axial  
19   movement only over a certain range where this range can be arranged to limit  
20   the stretch or compression of the corrugated tubular to prevent excess strain.

21       In another aspect, a cylindrical liner with a first and second end is  
22   provided on the exterior of a corrugated tubular joint with first and second  
23   ends where the first end of the liner is joined/fastened to the first end of the  
24   corrugated tubular joint and said liner extends to cover all or a portion of the

1   corrugated interval. This configuration permits telescopic sliding of the straight  
2   liner relative to the corrugated tubular to provide a system retaining the axial  
3   compliance of the corrugated tubular but having increased flexural stiffness  
4   and therefore buckling stability. In a further aspect of such a corrugated  
5   tubular with external liner the second end of the liner and second end of the  
6   tubular may be provided with interlocking stop rings or similar devices  
7   permitting the telescopic relative axial movement only over a certain range  
8   where this range can be arranged to limit the stretch or compression of the  
9   corrugated tubular to prevent excess strain.

10       In another aspect, the end sections of the forms may be configured to  
11   form expanded tubular intervals suitable for internal threading and thus  
12   simultaneously form a tubular article with corrugations and an integral box  
13   connection on one or both ends.

14       In another aspect, the forming vessel may be arranged as a split form.

15       In another aspect, the forming elements may be arranged to provide  
16   helical corrugations.

17       As an alternative embodiment, we believe an axially compliant tubular  
18   may be formed by providing forming elements arranged to create a double  
19   helix corrugation using left and right helixes. Such a geometry is similar to that  
20   occurring in diamond wall buckling of thin cylinders.

21       As an alternative embodiment, we believe the corrugation geometry  
22   may be further controlled by application of axial load subsequent to  
23   hydroforming where such load would typically be compressive.

1        As a further alternative embodiment to control corrugation geometry,  
2    we believe the forming process may be conducted with independent control of  
3    axial displacement as a function of forming fluid pressure or volume control.  
4    This embodiment requires the form to be arranged with the corrugating  
5    section having floating restraint rings confining the profiled split rings and at  
6    one of the end cylindrical sections arranged to telescope within the confining  
7    tube and on the mandrel. Control of the axial displacement of this telescoping  
8    end section with respect to the confining tube by means of a hydraulic ram or  
9    other suitable load application device then permits the desired independence  
10   of axial and pressure loads or displacements.

11        In another aspect, material may be placed in the space between some  
12   or all of the corrugations, either on the outside or inside, as a means to control  
13   or limit the compressive load displacement response of individual  
14   corrugations. Materials suitable for this purpose include plastic, cement, split  
15   sleeves, rings or springs which may be used separately or in combination with  
16   each other.

17        In another aspect, the corrugation amplitude at the ends of a  
18   corrugated interval may be ramped down over the last few corrugations to  
19   provide a more gradual axial stiffness contrast between cylindrical and  
20   corrugated tubular wall intervals.

1           **THE EMBODIMENTS OF THE INVENTION IN WHICH AN**  
2   **EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS**  
3   **FOLLOWS:**

4           1. In a string of joints of metal pipe extending through and being  
5   restrained by earth material, the string being subject to change in axial load  
6   subsequent to installation, each such joint comprising a tubular body having a  
7   side wall, the improvement comprising:

8           the body side wall of at least one such joint being formed into  
9   corrugations along at least part of its length;

10           the side wall having a diameter/thickness ratio less than 100;

11           the corrugations having a corrugation radius of curvature to thickness  
12   ratio less than 10.

13

14           2. The improvement as set forth in claim 1 wherein:

15           a plurality of such corrugated joints are spaced apart along the string.

16

17           3. The improvement as set forth in claim 1 wherein:

18           all of the joints of a section of the string are corrugated.

19

20           4. The improvement as set forth in claim 1 wherein:

21           the corrugations have a corrugation radius of curvature to thickness  
22   ratio less than 5.

1           5. The improvement as set forth in claim 1, 2, 3 or 4 wherein:

2           the corrugations of each corrugated joint have webs and peaks and the

3           webs have a maximum angle of at least 20° with respect to the axis of the

4           corrugated joint; and

5           the wall thicknesses of the webs of the corrugations are thinner than

6           the peaks.

7

8           6. The improvement as set forth in claim 1, 2, 3 or 4 wherein:

9           the corrugations of each corrugated joint have webs and peaks and the

10          webs have a maximum angle of at least 20° with respect to the axis of the

11          corrugated joint;

12          the wall thicknesses of the webs of the corrugations are thinner than

13          the peaks; and

14          the corrugated joint has been hydroformed while maintaining its original

15          length.

16

17          7 The improvement as set forth in claim 1 comprising an outer sleeve

18          containing the corrugations.

19

20          8 The improvement as set forth in claim 1 comprising:

21          a sleeve, internal of the corrugated joint, supporting the corrugations.

22

23          9 The improvement as set forth in claim 1 comprising:

24          rings positioned between the corrugations to limit compression.

1            10 In a string of joints of steel pipe positioned in a wellbore and  
2    extending through and being restrained by earth material, the string being  
3    subject to change in axial load arising from thermal expansion or contraction,  
4    each such joint comprising a tubular body having a side wall and threaded  
5    ends, the improvement comprising:

6            the body side wall of at least one such joint being formed into  
7    corrugations along at least part of its length;

8            the side wall having a diameter/thickness ratio less than 100;

9            the corrugations having a corrugation radius of curvature to thickness  
10   ratio less than 10.

11

12            11 The improvement as set forth in claim 10 wherein:

13            the corrugated joint has been hydroformed while maintaining its original  
14   length.

15

16            12. The improvement as set forth in claim 10 wherein:

17            a plurality of such corrugated joints are spaced apart along the string.

18

19            13. The improvement as set forth in claim 10 wherein:

20            all of the joints of a section of the string are corrugated.

21

22            14. The improvement as set forth in claim 10 wherein:

23            the corrugations have a corrugation radius of curvature to thickness  
24   ratio less than 5.

1           15. The improvement as set forth in claim 10, 11, 12, 13 or 14

2   wherein:

3           the corrugations of each corrugated joint have webs and peaks and the  
4   webs have a maximum angle of at least 20° with respect to the axis of the  
5   corrugated joint.

6

7           16. The improvement as set forth in claim 10 comprising an outer  
8   sleeve containing the corrugations.

9

10          17. The improvement as set forth in claim 10 comprising:

11          a sleeve, internal of the corrugated joint, supporting the corrugations.

12

13          18. The improvement as set forth in claim 10 comprising:

14          rings positioned between the corrugations to limit compression.

15

16          19. The improvement as set forth in claim 10, 11, 12, 13 or 14

17   wherein:

18          the string is used in connection with a wellbore used in a thermal  
19   process;

20          the corrugations of each corrugated joint have webs and peaks and the  
21   webs have a maximum angle of at least 20° with respect to the axis of the  
22   corrugated joint; and

23          the wall thicknesses of the webs of the corrugations are thinner than  
24   the peaks.

1           20. A joint of steel pipe comprising:  
2           a tubular body having a side wall and threaded ends;  
3           part of the body side wall between the ends having been hydroformed  
4           into corrugations while maintaining its original length;  
5           the side wall having a diameter/thickness ratio less than 100;  
6           the corrugations having a corrugation radius of curvature to thickness  
7           ratio less than 10.

8

9           21. The joint as set forth in claim 20 wherein:  
10           the corrugations have a corrugation radius of curvature to thickness  
11           ratio less than 5.

12

13           22. The joint as set forth in claim 21 wherein:  
14           the corrugations have webs and peaks and the webs have a maximum  
15           angle of at least 20° with respect to the axis of the joint.

16

17           23. The joint as set forth in claim 21 or 22 wherein:  
18           the wall thicknesses of the webs of the corrugations are thinner than  
19           the peaks.

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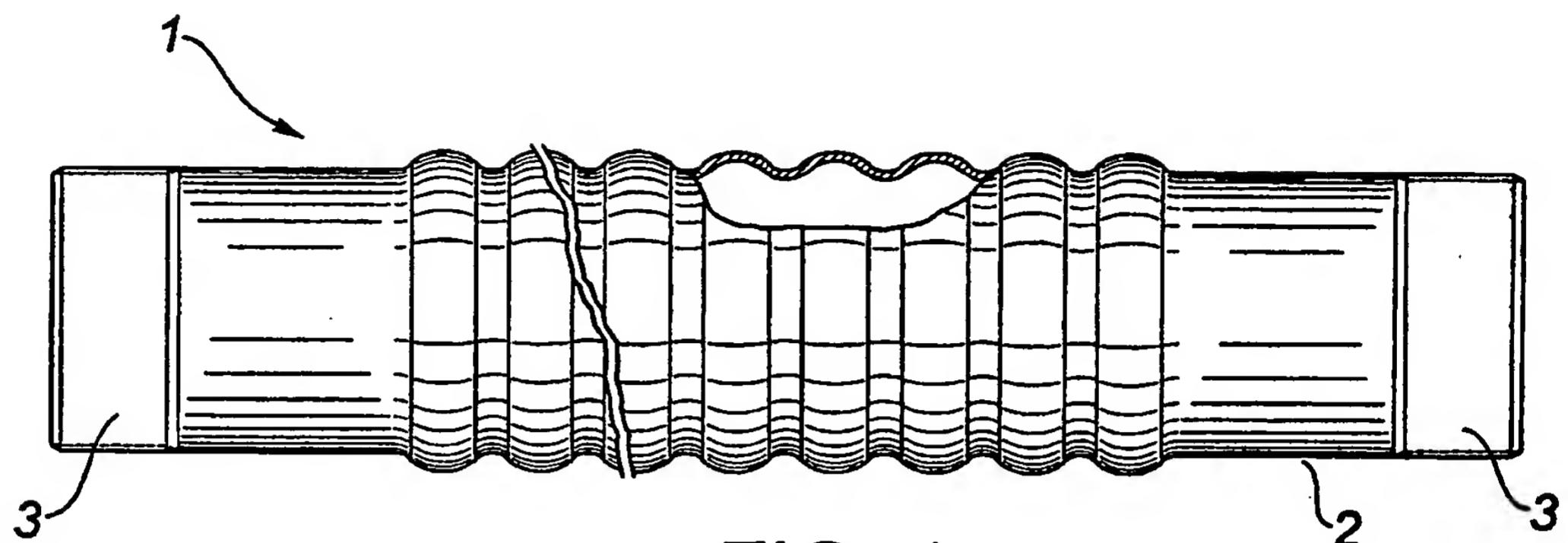


FIG. 1

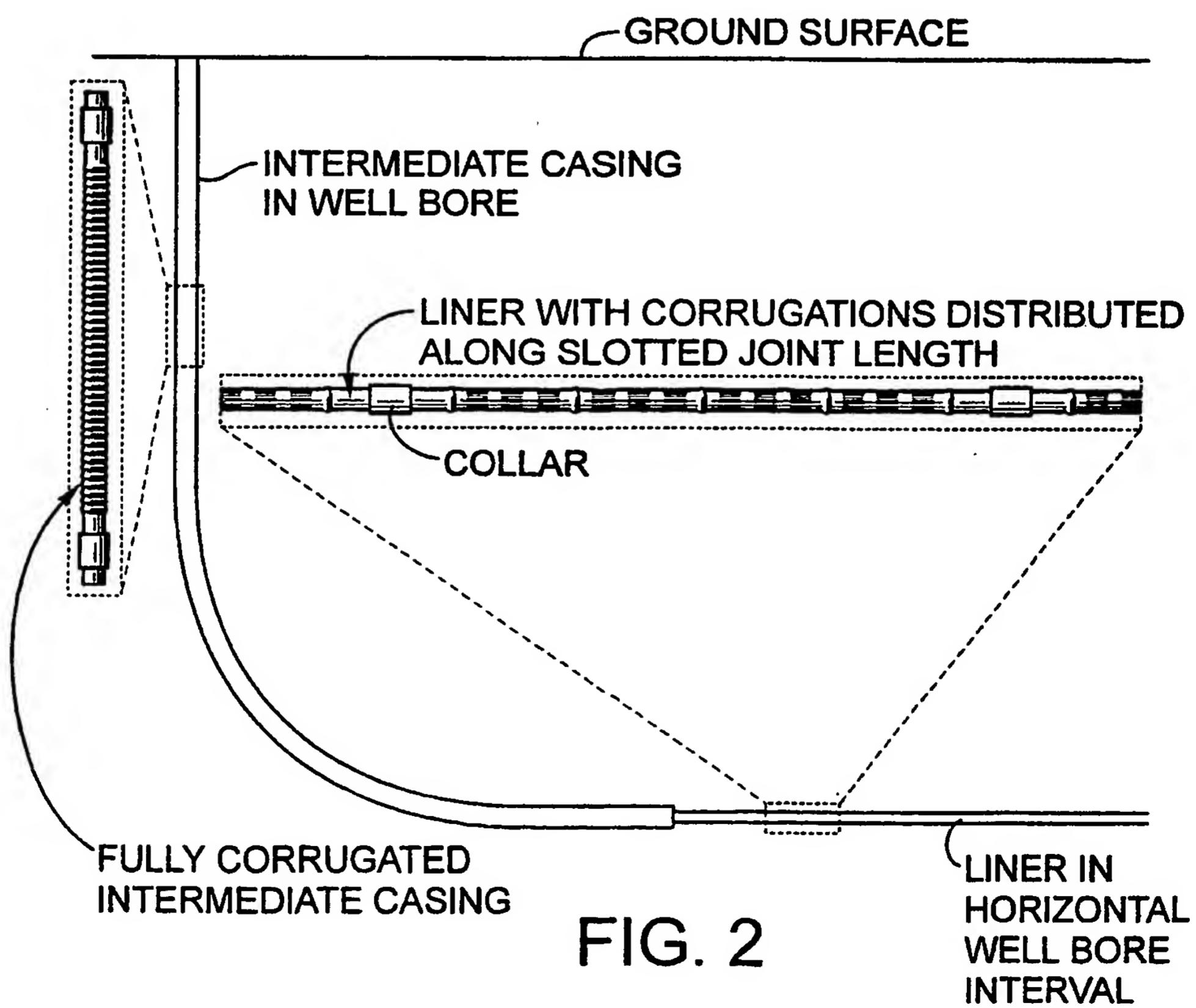


FIG. 2

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FIG. 3



FIG. 4

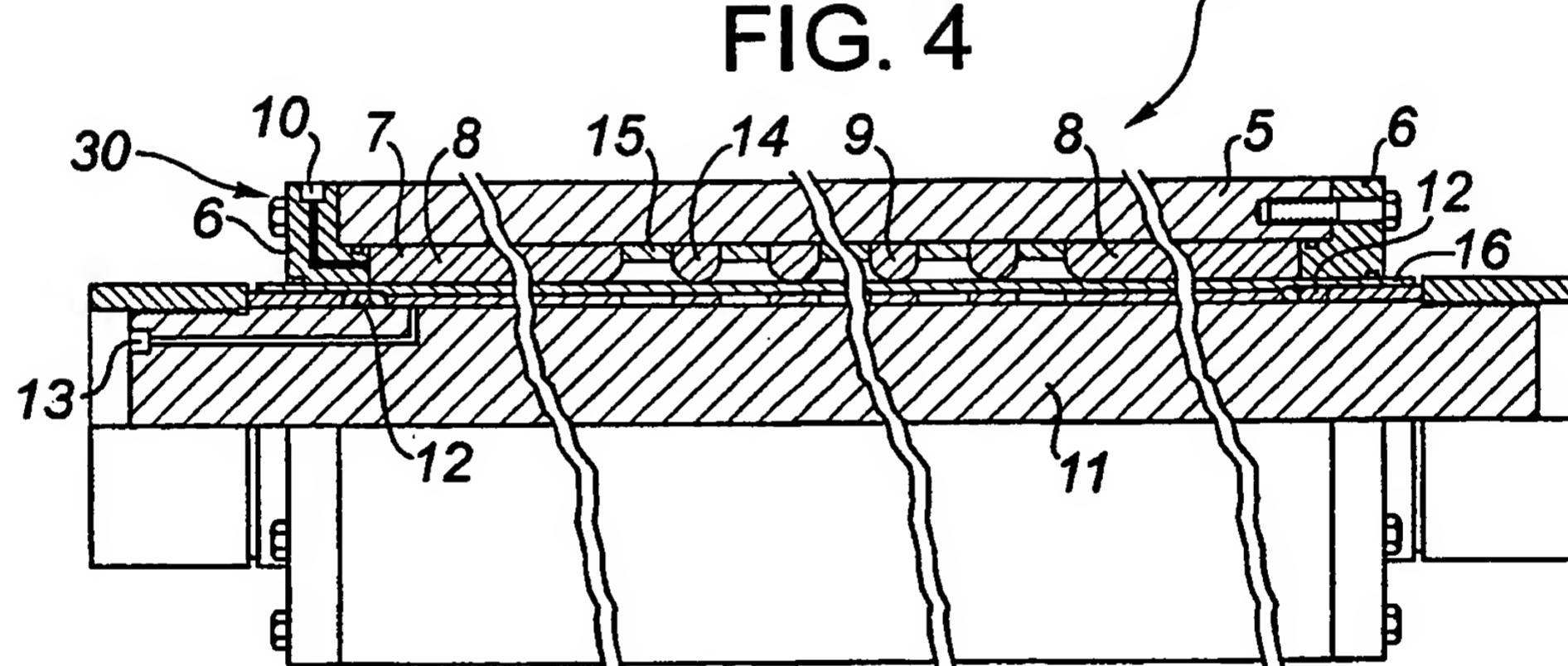
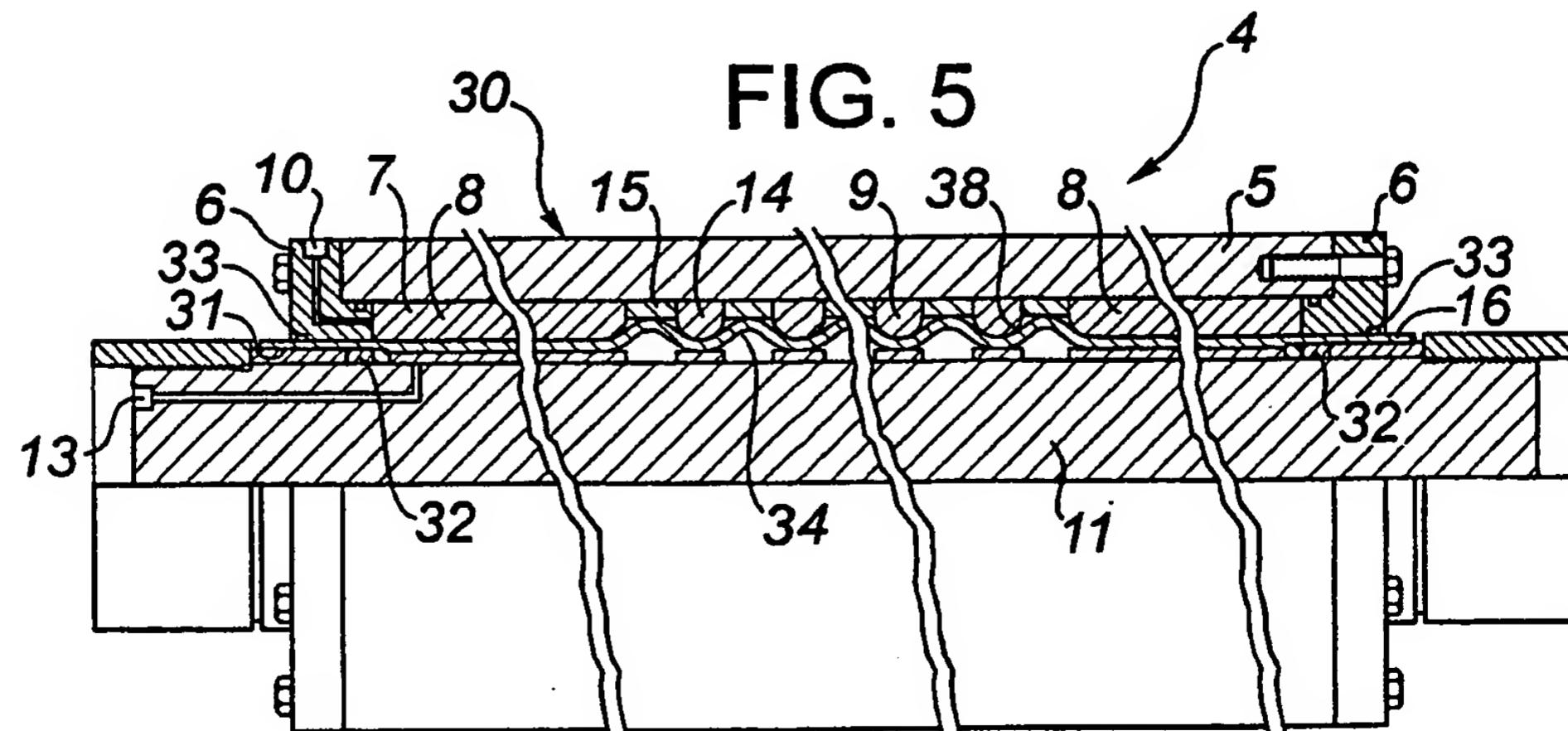


FIG. 5



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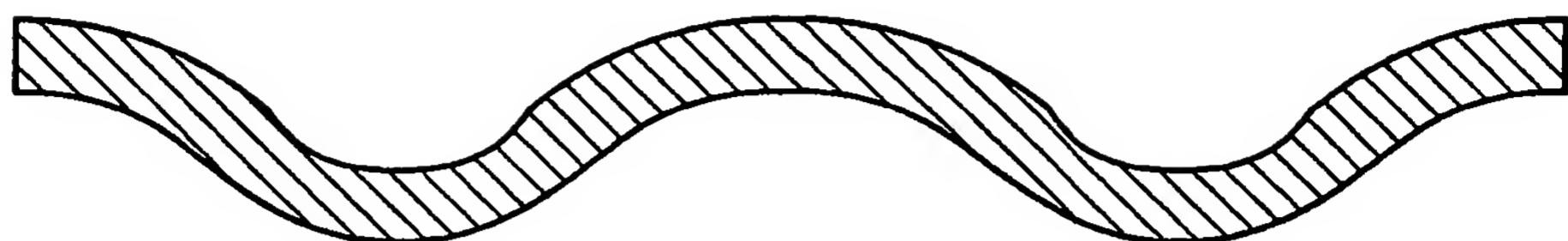


FIG. 6

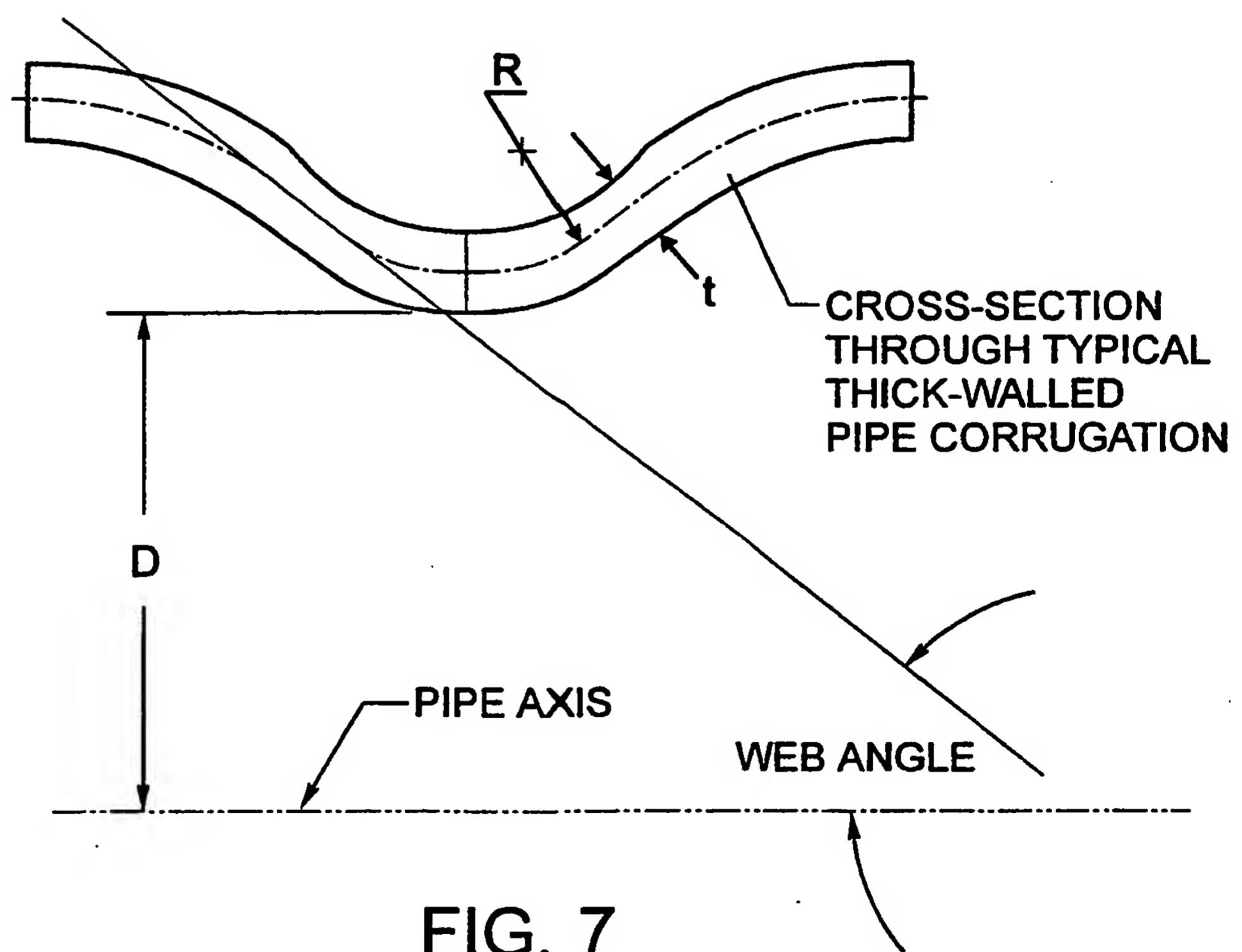


FIG. 7

# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/CA 00/00502

**A. CLASSIFICATION OF SUBJECT MATTER**  
IPC 7 B21D15/10 E21B17/00

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 B21D E21B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EP0-Internal

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 026 209 A (TITMAS JAMES A ET AL) 25 June 1991 (1991-06-25) column 3, line 42 - line 48 ---	1-23
A	FR 2 050 311 A (BUTIN GILLET ETS) 2 April 1971 (1971-04-02) page 1, line 18 - line 23 -----	1-23

Further documents are listed in the continuation of box C.

Patent family members are listed in annex.

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- "A" document defining the general state of the art which is not considered to be of particular relevance
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"&" document member of the same patent family

Date of the actual completion of the international search

13 July 2000

Date of mailing of the International search report

20/07/2000

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,  
Fax: (+31-70) 340-3016

Authorized officer

Garrido Garcia, M

# INTERNATIONAL SEARCH REPORT

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A. CLASSIFICATION OF SUBJECT MATTER	IPC 7 B21D15/10 E21B17/00
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According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 B21D E21B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

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- "&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
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13 July 2000

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Name and mailing address of the ISA

European Patent Office, P.O. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,  
Fax: (+31-70) 340-3016

Authorized officer

Garrido Garcia, M

